Design and Analysis of TEM Horn antenna for GPR applications

A Thesis submitted in partial fulfillment

of the Requirements for the degree of

Master of Technology

in

Electronics and Communication Engineering

Specialization: Communication and Networks

By

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Under the guidance of

Prof. Subrata Maiti

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Dedicated to my Parents and well-wishers...

Dept of Electronics and Communication Engineering
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Certificate

This is to certify that the work in the thesis entitled **Design and Analysis of TEM Horn antenna for GPR applications** by **Ajay kumar Badita** is a record of an original research work carried out by him during 2014 - 2015 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology in Electronics and Communication Engineering (Communication and Networks), National Institute of Technology, Rourkela. Neither this thesis nor any part of it, to the best of my knowledge, has been submitted for any degree or academic award elsewhere.

Place: NIT Rourkela
Date: 2nd June 2015

Prof. Subrata Maiti
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Abstract

Ground penetrating radar (GPR) is a technique used to probe the ground.This technique is positioned top among all existing geophysical techniques.Applications of GPR are enormous and are ranging from planetary exploration to the detection of buried mines.

In GPR to get high resolution and to get the wave traveled through deeper distance inside the earth, the transmitting antenna (Tx) must transmit the narrow width pulse signal into the ground where objects are hidden. This thesis presents the work on the design of TEM horn antenna. For this application A Compact Double-Ridged Horn Antenna from the family of horn antennas with an ultra wide band (0.827-4.5)G Hz is designed & simulated.Both the time domain and frequency domain requirements are satisfied by this antenna. This antenna is simulated using Computer simulation technology (CST) microwave studio. This antenna is test simulated in time domain solver with feeding via 50 Ω SMA and also tested in both thermal solver & mechanical solver to check for its malfunction. The variation of characteristic impedance across the antenna structure is gradually varied from 50 Ω to 377 Ω.

In this thesis we will go through the steps how the lower range frequencies can be achieved with TEM horn & in what way the Linear TEM horn is transformed to Compact Double-Ridged Horn Antenna. This thesis also includes an explanatory part on both theoretical & simulated version of Linear TEM horn antenna, Double ridged horn antenna, Compact Double-Ridged Horn Antenna & Double-Ridged Horn Antenna in GPR scenario along with the simulation results.

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1 Introduction

1.1 Background

Ground penetrating radar techniques are increasingly being used to detect and find location of buried objects and structures remotely that are hidden beneath the earths surface.Ground penetrating radar technique is also known as Ground probing radar, subsurface radar, surface penetrating radar (SPR).

The first use of electromagnetic signals to determine the presence of remote terrestrial metal objects is generally attributed to Hiilsmeyer in 1904, but the first description of their use for location of buried objects appeared six years later in a German patent by Leimbach and Lowy[1]. Their technique consisted of burying dipole antennas in an array of vertical boreholes and comparing the magnitude of signals received when successive pairs were used to transmit and receive. In this way, a crude image could be formed of any region. These authors described an alternative technique, which used separate, surface-mounted antennas to detect the reflection from a sub-surface interface. An extension of the technique led to an indication of the depth of a buried interface, through an examination of the interference between the reflected wave and that which leaked directly between the antennas over the ground surface.The main feature of this work is continuous wave (CW) operation.

The work of Hiilsenbeck in 1926 appears to be the first use of pulsed techniques to determine the structure of buried features. He noted that any dielectric variation, not necessarily involving conductivity, would also produce reflections and that the technique, through the easier realisation of directional sources, had advantages over seismic methods.

Renewed interest in the subject was generated in the early 1970s when lunar investigations and landings were in progress. For these applications, one of the advantages of ground penetrating radar over seismic techniques was exploited, namely the ability to use remote, noncontacting transducers of the radiated energy, rather than the ground contacting types needed for seismic investigations.

From the 1970s until the present day, the range of applications has been expanding steadily, and now includes building and structural nondestructive testing, archeology,road and tunnel quality assessment, location of voids and containers, tunnels and mineshaft, pipe and cable detection, as well as remote sensing by satellite[2].

Future trend in GPR is to create a Purpose-built equipment for each of the above applications and the user now has a better choice of equipment and techniques.

Different technologies other than GPR are

- seismic
- electrical resistivity
- gravity sensing
- magnetic surveying
- radio metric
- thermographic
- electromagnetic methods

GPR is is one of the special practicing area than all other because it includes a range of specializations such as

- EM wave propagation study in lossy media

- UWB technology can be used with the antenna
- Radar system design
- Discriminant waveform signal processing
- Image processing

An overall design strategy is outlined, together with a more detailed treatment of a range of topics which are relevant to effective subsurface radar operation. These include the dielectric properties of earth materials, signal modulation schemes, design and construction of suitable antennas. Finally, an assessment is made of future prospects, both technically and commercially for this developing area of radar technology.

Most of GPR systems are based on impulse radar technology. In this technology the transmitting (Tx) antenna sends an impulse to ground surface below which the targets are hidden. This electromagnetic wave can efficiently penetrate the surface if it is coupled to ground. Thus, it is one of the main intentions of many antenna designers to couple the Tx antenna and the ground. The target reflects and scatters the radiated electromagnetic impulse, based on the dielectric discontinuities with the soil. Then, the receiving antennas (Rx) collect the back-scattered signal partially. This back-scattered signal will be extracted by signal and image processing techniques to visualize the target in an user-friendly manner. So, in parallel to this field of research, improvements in signal and image processing techniques help realizing the idea of fast-recovery high-resolution GPR, eventually.

The targets might be located at any depth beneath the ground surface depends on the particular application. The detection depth, as an important feature, relies on the low frequency components of the radiated pulse due to the fact that these low frequency components penetrate more inside the soil. Higher frequency components, on the other hand, increase the resolution. Hence, the desired resolution can be obtained if a sufficient bandwidth is chosen. Over the years, GPR has been shown as an UWB system which is more challenging than ordinary radar systems due to the higher clutter-to-signal ratios. Recently developed GPR systems have higher speed, higher resolution and cheaper prices.

Research in this direction mainly focuses on obtaining a fast recovery accurate-enough images from buried objects,indeed.

Applications of GPR are in a vast group from commercial ones such as utility pipes and cables detection, to military ones such as anti-personnel and anti-tank land-mines detection, to archaeological investigations, to Geophysical investigations, to oil and gas explorations and so forth. Apart from the direct applications and benefits, the investigation in this vibrant field of research can be applied to and helps maturing other radar technologies such as medical imaging and through-wall detection, and vice versa.

1.2 GPR technology

GPR has an enormously wide range of applications, ranging from planetary exploration to the detection of buried mines. The selection of a range of frequency operations, a particular modulation scheme, and the type of antenna and its polarization depends on a number of factors, including the size and shape of the target, the transmission properties of the intervening medium, and the operational requirements defined by the economics of the survey operation, as well as the characteristics of the surface. The specification of a particular type of system can be prepared by examining the various factors which influence directivity and resolution[3].

Basic Principle

Ground Penetrating Radar (GPR) uses a UWB frequency signal that is transmitted into the ground.The reflected signals are then returned to the receiver and stored on digital media for signal processing. The computer measures the time taken for a pulse to travel to and from the target which indicates its depth and location. The reflected signals are interpreted by the system and displayed on the unit's LCD panel.

Figure 1.1: Basic principle

Figure 1.2: GPR data collection (below ground)

GPR Data Collection (below ground)

In order to find the location and depth of an object, buried subsurface, various types of GPR equipment are used to collect the data. The type of GPR equipment required is dependent on the depth and size of the target to be located. The radar unit emits and receives reflected signals up to a thousand times per second. These signals are viewed by the field operator on location immediate analysis and are also stored in the system and downloaded to a computer for further data analysis if required.

GPR Data Collection (in concrete)

To locate objects such as rebar, conduits and post-tension cables imbedded in concrete a high frequency GPR system is used. The data can be collected in simple line scans to determine the thickness of concrete or in a grid format which will produce a map of any targets located in the concrete. Using this method we can look at virtual slices in the image to determine the depth of the objects and create a 3D map of the image.

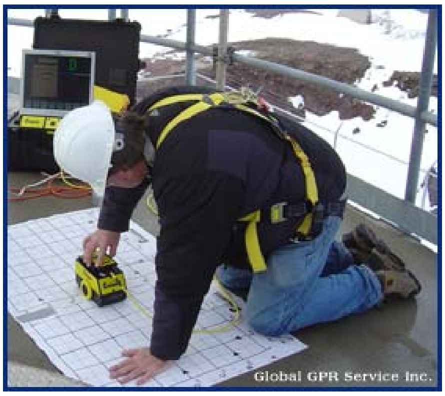

Figure 1.3: GPR data collection (in concrete)

GPR Data Analysis

GPR waves travel through many different materials. Different types of soil, concrete, fill material, debris, and varying amounts of water saturation all have different dielectric and conductive properties that affect the GPR waves, and thus GPR data interpretation. Although the data images are displayed on the screen they still require someone with field experience to interpret them in order to accurately determine the findings.

How Deep Can It Go?

This is probably one of the most commonly asked questions. In most cases an estimated depth range can be determined with accuracy based upon the subsurface material and the frequency of the GPR antenna. For applications requiring higher resolution, such as locating rebar or conduits in concrete, a higher frequency GPR system (1,000 MHz) is used. This will give high resolution detail

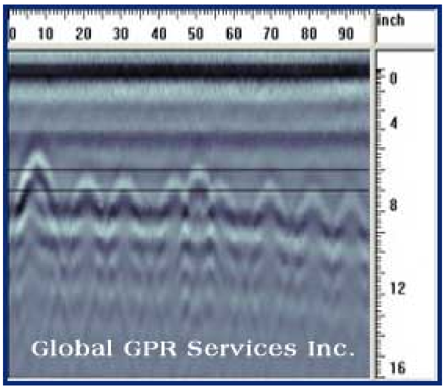

Figure 1.4: GPR data analysis

Figure 1.5: GPR depth chart

for down to approximately 24 inches in depth. Applications which require deeper penetration in ground soil requires a lower frequency (12.5 MHz to 500 MHz). Depending on the subsurface material the depth range can be from a few inches to thousands of feet (as indicated in the chart:1.5].

1.2.1 Types of GPR

Depending on the manner in which data are acquired, GPR can be designed as time domain GPR and frequency domain GPR. In time domain, data received is function of time interval, a time pulse of short duration at some pulse repetition frequency is sent to the ground and a backscattered pulse corresponding to the transmitted pulse is intercepted by receiving antenna.

In frequency domain, data recorded varies according to the frequency used for transmission. Frequency can be transmitted continuously or in discrete steps with continuity over discrete interval for the frequency band used for GPR application.

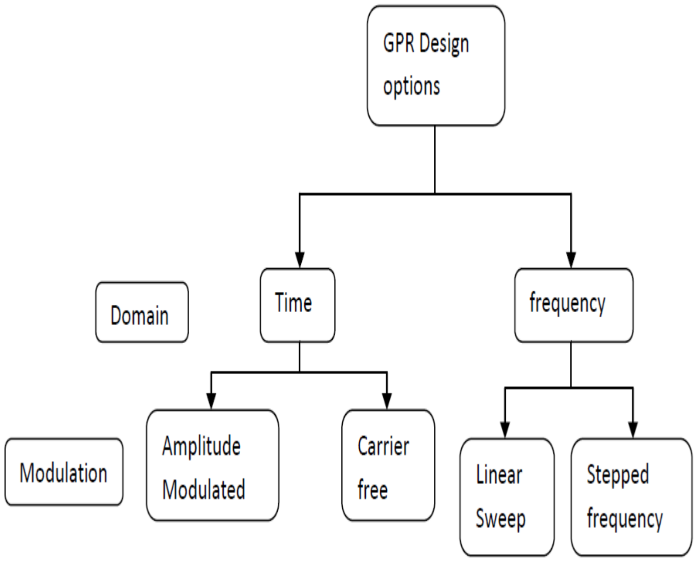

Figure 1.6: GPR system classification

Two main categories of GPR:

- Time domain radar
- Frequency domain radar

Impulse Radar

Radar that acquire data in time domain are known as Impulse. Pulse transmitted in time domain & reflected energy is received as a function of time.

Resulting waveform indicates amplitude of energy scattered form subsurface objects vs time. Range of information is based on time of flight.Display unit to measure Amplitude vs Range is A-scope.

Advantages of Impulse radar:

- Simplicity if generating impulse
- Low-cost parts

Disadvantages of Impulse radar:

- Undesirable ringing
- inefficient use of transmitted power
- Resolution is limited by pulse width

Stepped Frequency radar

It is a continuous wave radar technique since wave energy is transmitted and received continuously. It consists of Radio frequency source, receiver and digital signal processor (DSP). The source is allowed to step between a start frequency f_o and a stop frequency f_{N-1} in equal and linear increments, where N is total number of increment value of frequency. Hence in SFCW technique, frequency is divided in number of steps over the band of operation.

Each segment is transmitted continuously, while transmission is discrete for the overall bandwidth. Hence a narrow band coherent receiver can be used for GPR reflected wave energy reception. By heterodyning a port of the transmitted signal with received signal, a composite signal called return signal is formed which is digitized for each interval and stored in discrete form for further processing. When a full sweep of N steps is complete, a frequency domain tool called Inverse Discrete Fourier transform is operated to change the collected discrete data from frequency domain to time domain. This inverse operation gives a time domain synthesized pulse. It has improved dynamic range.

Target range information is contained in 'time of flight′ of the wave, which is actually a phase path difference measurement. If target is closer to the GPR system, smaller phase change between the transmitted and received signal is observed as the travelling path of wave energy is shorter. But if the target is sufficiently apart, a larger phase change is observed due to longer propagation path.

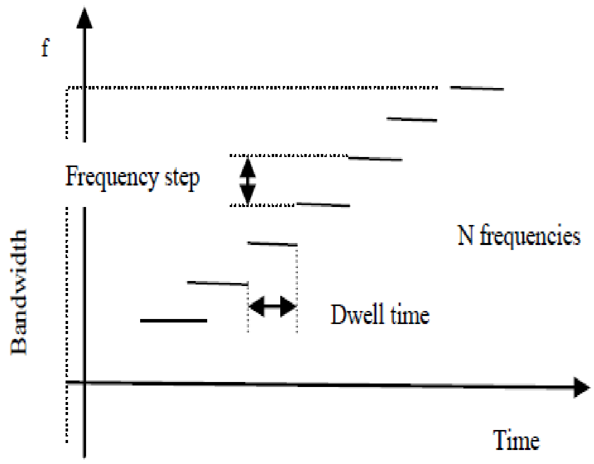

Figure 1.7: Stepped frequency continuous wave Radar

The amplitude of the EM signal received is a function of the radar cross section of the target, the range i.e. height below the ground level (vertical range) and the propagation loss of the ground.

Advantages of SFCW radar:

- Frequency transmission can be controlled
- Efficient use of power
- Efficient sampling of wideband signals with ADCs

Disadvantages of SFCW radar:

- Complex electronics involved
- Requirement of DSP

1.2.2 GPR system parameters

Some design parameters In the design of a time domain GPR, there are certain parameters that can be set as a function of the application[4]. In the following part we discuss several of these parameters. It is important to understand the influence of the parameters on the data and the acquisition time as in commercial systems they can generally be set by the user.

a) Frequency range & Range resolution :

The choice of the central frequency and of the bandwidth of the GPR is an important issue, and depends primarily on the type of application. For each application a set of frequency constraints can be developed. The parameters influencing the frequency range are: the size of the object, the wanted depth resolution, the maximal penetration depth, and the properties of the soil.

$$B = \frac{1}{\tau_p} \qquad for\ impulse \tag{1.1}$$

$$B = (f_{max} - f_{min}) \qquad for\ CW \tag{1.2}$$

The basic criterion for depth resolution is that the spatial separation between two events (discontinuities in dielectric constant) must be equal to the spatial half-width of the incident pulse. Notice that the half-width in this definition has to be considered in the ground, where the velocity of propagation v is smaller than in free space, so that the pulse width in the ground is smaller than in free space. The depth resolution is given by equation 1.3

$$R_{res} = \frac{(1.39)c}{2B\sqrt{\epsilon_r}} \tag{1.3}$$

In Table 1.8 depth resolution is given for a mono-cycle GPR in two different kinds of ground: respectively with a ϵ_r of 4 (sandy dry soil) and ϵ_r of 15 (sandy wet soil). In the case of a mono-cycle the pulse-width is 1/fc.

In conclusion, for good depth resolution, short pulses are needed, which means larger bandwidth. The depth of penetration strongly decreases for higher frequencies in a given soil. The electrical properties of the soil together with the wanted maximum depth penetration imply an upper limit for the used frequencies. Once frequencies above 1 GHz are used, depth penetration decreases dramatically. So if large penetration depth is needed, lower frequencies are preferred. Besides depth resolution and attenuation, there is also the problem of clutter. Clutter can be

Central frequency	Pulse-width	Depth resolution	
		ε_r =4	ε_r =15
500 MHz	2 ns	15 cm	7.7 cm
1GHz	1 ns	7.5 cm	3.9 cm
2GHZ	0.5 ns	3.75 cm	1.9 cm
3GHz	0.33 ns	2.5 cm	1.3 cm

Figure 1.8: GPR depth chart depth resolution versus central frequency

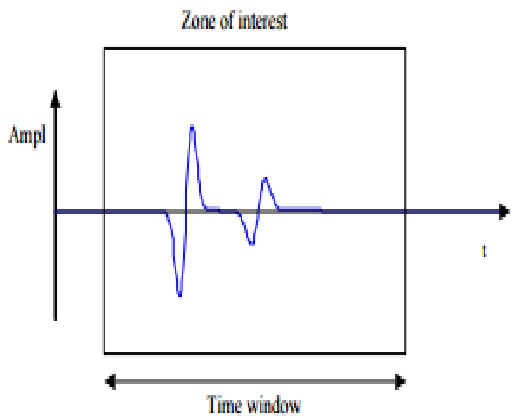

Figure 1.9: Timing window

defined as backscattered signals that are not from possible targets of interest, but occur in the same time window and have similar spectral characteristics. The smaller the wavelengths in the emitted pulse the larger the quantity of possible clutter sources in the heterogeneous ground. As a general rule it is desirable that the wavelength of the central frequency in the ground of the GPR is ten times larger than the size of the heterogeneities in the ground to reduce clutter. This also sets a constraint for high frequencies.

b) Time window :

The time window represents the zone of interest that is to be sampled or in other words, the duration of one A-scan. The beginning and the duration of the timing window can be set by the slow and the fast ramp timing signals.

In the application of antipersonnel mine detection the zone of interest is the top layer of the ground, between 0 and 20 cm of depth. The duration of the time window Tg is in direct relation with the maximal depth of investigation S_{max} by

$$S_{max} = \frac{v.T_g}{2} \tag{1.4}$$

The problem is that the velocity of propagation depends on the permittivity of ground. The velocity of propagation in the ground is approximately given by

$$v' = \frac{c}{\sqrt{\epsilon_r}} \tag{1.5}$$

In the next Table some worst case values of Tg are represented in function of S_{max} for a velocity of propagation of c/5.If mines are not deeper than 20 cm, a time window of 10 ns must be sufficient.

s_{max}(cm)	T_g(ns)
18	6
30	10
60	20

Figure 1.10: Maximal depth of investigation

c) Equivalent sampling period :

The equivalent sampling period indicates the period at which one would have to sample with a conventional A/D converter. In the case of a sequential sampler,the equivalent sampling period is ΔT. In order to do an acquisition without any loss of information one has to respect Shannon′s theorem. This means that the equivalent sampling frequency (=1/ΔT) has to be at least twice the highest significant frequency in the emitted signal. In practice however the equivalent sampling frequency is taken much higher than two times the highest significant frequency in the emitted pulse. Typical values of ΔT in GPR applications are 10 -100 ps.

d) Pulse Repetition Frequency (PRF) :

In classic air radar, the PRF is limited by the maximal range at which one wants to detect targets, i.e. the maximum unambiguous range. Indeed all echos from possible targets must be returned before the next pulse is emitted by the radar, otherwise the interpretation of range is incorrect. In GPR technology this is not really a problem. The maximum depth of investigation in the ground is usually limited by the attenuation of the ground and as a consequence will put no restriction on the choice of the PRF. In practice the PRF will be limited by the transmitter technology. A sequential sampler takes one sample after each emitted pulse, so the PRF will influence the acquisition time of one A-scan. The PRF will also determine the mean power of the GPR pulse generator for a given peak power. Typical values of PRF are 100-1000 kHz. If 512 points are acquired per A-scan, the acquisition of one A-scan would take between 5.12 ms and 0.512 ms.

e) Averaging or stacking :

In general the noise in the received signal can be reduced by averaging (also called stacking) a number of A-scans. Averaging S A-scans means a noise reduction in amplitude by S or an improvement of the signal to noise ratio (SNR) by 10log(S). Normally the stack number S can be set during acquisition or stacking can be done off-line. When setting the stack number during acquisition, the GPR will automatically output an A-scan which is the average of S A-scans. Choosing S too high will considerably slow down acquisition, as well as the maximum displacement speed of the radar for a given grid (or resolution) on the ground. Typical values of S in GPR applications are 8 - 32, depending on the amplitude of the emitted pulse.

f) Dynamic Range :

The radar receiver must be capable of handling large signals from surface reflections and shoe=rt-range target and also detect small near the noise floor. The ratio of the largest receivable signal to the minimal detectable signal is called the dynamic range and is defined as follows:

$$Dynamic\ Range = 20 \log \frac{V_{max}}{V_{min}} \tag{1.6}$$

It is usually expressed in decibles (dB) fora specific bandwidth signal bandwidth in hertz. The largest receivable signal, V_{max} must not overload the radar front end.The minimal detectable signal V_{min} must be above the receiver noise level and have a minimum signal-to-noise ratio (SNR) to be detected.Typically, radars will have a greater system dynamic range than sampling dynamic range.

g) Unambiguous range :

The furthest distance that a target can be determined without aliasing occurring is called unambiguous range, R_{max}. To avoid aliasing, the reflected energy should be received within the time period or range cells of its associated transmit pulse and before the next transmit pulse.

For an impulse GPR, the PRI determines the maximum unambiguous range:

$$R_{max} = \frac{c.T_r}{2\sqrt{\varepsilon_r}} \tag{1.7}$$

For a stepped-frequency CW (SFCW) radar, the unambiguous range can be calculated from the following equation:

$$R_{max} = \frac{N_c}{4B\sqrt{\varepsilon_r}} \tag{1.8}$$

h) Scanning speed :

The inspection of railways ballast by use of ground penetrating radar devices has been performed for several years now. The operation of horn antennas avoids this problem because they can be mounted about half a metre above the ballast.

The development of a new 400 MHz horn antenna for railways ballast and subsoil inspection was additionally triggered by the availability of new GPR control units like the GSSI SIR-20. These units allow data collection rates of several hundred scans per second with a time resolution of 5 picoseconds for 512 or 1024 samples per scan. Using the 400 MHz horns with 50 nanoseconds time range offers survey velocities of more than 100 km/hour with 20 scans per metre. This scan separation has been identified to be an important parameter for good data quality. Less scans per meter would mean less information between the sleepers.

i) Power :

GPR equipment can be run with a variety of power supplies ranging from small rechargeable batteries to vehicle batteries and normal 110/220-volt.

1.2.3 Problem areas in GPR

GPR systems are similar to conventional radar systems in the sense that both measure target range i.e. radial distance of the target from the system irrespective of the direction by determining the two way travel time of an electromagnetic wave. Practically, however GPR systems are more complicated than conventional (ordinary) radar systems due to some unique problems associated with transmitting and receiving Electromagnetic energy through a subsurface medium. The main technical challenges in design and application of a Ground Penetrating Radar are:

- Modelling GPR signal propagation in complex geometry
- Modelling Antenna placed near to the earth sub-surface
- Processing GPR data to detect target with low false alarm rate
- Achieving high scanning speed
- Implementing low cost hardware for realizing GPR system
- Designing suitable antenna for efficient coupling of GPR signal

1.3 Objective of the thesis

The objective of the research work is summarized as follows :

An ultra short pulse is radiated from the Tx antenna and a reflected pulse from the target will be captured by Rx antennas. The main objective of the thesis is to design (or improve) the high performance Tx antenna for this GPR system such that the radiated impulse on the ground correlates to the radiated pulse highly and without late time ringing. In reality, higher than 95 % correlation and less than –20dB with respect to the highest peak-to-peak value of the pulse are the acceptable measures for this GPR. Also, the operating frequency range of the antenna should be specified. Due to the fact that the depth of targets are a few meters, the low frequency should be <1GHz. On the other side, resolution of the radar is guaranteed by ultra wide frequency bandwidth of the transmitted pulse. To meet the depth and the resolution requirements at the same time, the antenna should operate from a lower frequency 0.5 GHz to a higher frequency 6 GHz and greater. This means the return loss in this frequency band should be lower than –10 dB.

Challenges involved in designing antenna are:

1) Proximity Effect/Resistive loading technique
2) Efficient Coupling
3) Dispersion less antenna for time domain GPR application

1.4 Thesis format

This thesis is composed of four chapters.The background details of Ground Penetrating Radar (GPR), its functions and roles, basic technology and important problem areas are discussed in the current chapter. The objective for this thesis work is written after introduction part. This chapter ends with the outline of the thesis.

Chapter-2 Antenna theory & Design techniques

This chapter discusses in detail of the antenna theory & Design techniques, key features of GPR antenna. TEM Horn antenna basic theory is explained in this chapter. Resistive loading technique is discussed in this chapter.

Chapter-3 Methodology

Literature survey done for searching better antenna is mentioned in this chapter. This chapter contains the list of antennas both planar & TEM horn along with some techniques of immersing the antenna in a dielectric. The final approach done for the designing is mentioned at the end of this chapter.

Chapter-4 Field solver simulation

This chapter includes the implementation of three TEM Horn antennas namely Linear TEM Horn antenna(LTEM), Double ridged TEM Horn antenna (TEM DRH), Compact Double ridged TEM Horn antenna (CTEM DRH). Comparison of all the simulation results of above three antennas is mentioned.seperate discussion is made for the simulation results of both Thermal & Mechanical solver.

Chapter-5 Conclusion and Scope of Future work

This last chapter consists of conclusion and scope of future work in designing the Gorund penetrating Radar antenna.

2
Antenna theory

2.1 Introduction to Antenna theory

Antenna modelling should be done on the basis of propagation path, ground media, and frequency of operation. The propagation path consists in general of a lossy, inhomogeneous dielectric, which, in addition to being occasionally anisotropic, exhibits a frequency dependent attenuation and hence acts as a low pass filter. The upper frequency of operation of the system, and hence the antenna, is therefore limited by the properties of the material. The need to obtain a high value of range resolution requires the antenna to exhibit ultra-wide bandwidth and in the case of impulsive radar systems, linear phase response[5]. Types & classes of antennas that can be used are therefore limited. The following factors have to be considered in the selection of a suitable design

- large fractional bandwidth
- low time side lobes in the case of separate transmit and receive antennas
- low cross coupling levels

Where the radar system is a time domain system that applies an impulse to the antenna, the requirement for linear phase response means that only a limited number of types of antenna can be used unless the receiver uses a matched filter to deconvolve the effect of the frequency dependent radiation characteristics of the antenna. Where the radar system is frequency modulated or synthesized, the requirement for linear phase response from the antenna can be relaxed and log periodic, horn or spiral antennas can be used as their complex frequency response can be corrected if necessary by system calibration.

2.2 Key features of GPR antenna

An ultra short pulse is radiated from the Tx antenna and a reflected pulse from the target will be captured by Rx antennas. The main objective of the thesis is to design (or improve) the high performance Tx antenna for this GPR system such that the radiated impulse on the ground correlates to the radiated pulse highly and without late time ringing. In reality, higher than 95% correlation and <20dB with respect to the highest peak-to-peak value of the pulse are the acceptable measures for this GPR. Also, the operating frequency range of the antenna should be specified. Due to the fact that the depth of targets are a few meters, the low frequency should be <1GHz. On the other side, resolution of the radar is guaranteed by ultra wide frequency bandwidth of the transmitted pulse. To meet the depth and the resolution requirements at the same time, the antenna should operate from a lower frequency 0.5 GHz to a high frequency 6 GHz and greater. This means the return loss in this frequency band should be lower than –10 dB.

Apart from these strictly defined features, there are a few features that the antenna should posses. These are not quantized i.e., it is better to have an antenna with these qualities than without them. For example, to radiate one narrow pulse towards the ground, the Tx antenna should not distort the deriving pulse. Thus, it is better if the antenna radiates different frequency components of the pulse almost in the same spot i.e, it should have a fixed phase center.

Furthermore, it is preferable that the Tx antenna has a stable and flat gain as well as constant group delay. The former is important to assure that the radiated pulses have the same peak-to-peak level on the ground. Hence, the reflected pulses from the ground would not have been affected by the variation of the antenna gain instead of the contrast in permittivities. The latter is, also, important to keep the pulse width as narrow as the deriving pulse.

Another feature, the Tx antenna should better possess, is the linear polarization of the transmitted pulse. Low cross-polarization should be taken into account in order to obtain more accurate information regarding the direction and the shape of the target. Last but not least, the antenna should be feasible to manufacture with respect to the dimensions and the materials which are used in the design of the antenna.

2.3 Types of GPR antenna

Ultra-Wide Band (UWB) GPR system that transmits short time impulse signal is used to benefit from both low and high frequencies . The impulse waveform is generally Gaussian shaped monocycle type in time with the application oriented pulse durations from a few nanoseconds to a few hundred picoseconds which corresponds to a broadband spectrum from 100 MHz to 5 GHz (up to 10 GHz for stepped-frequency GPR). In this case, the convenient design of UWB Transmitter and Receiver (T/R) antennas is one of the most important parameters for the detection quality of impulsive GPR system. It is desired that the antennas have flat and high directivity gain, narrow beam, low side lobe and input reflection levels over the operational frequency band for the largest dynamic range, best focused illumination area, lowest T/R antenna coupling, reduced ringing and uniformly shaped impulse radiation. Furthermore, EM coupling effects between the transmitter and its receiver (or other receivers for array designs) and adaptive designs for EMI sensor (metal detector) mounted operations should also be considered[6]. Because of its light weight and relatively small size requirements, the hand-held GPR system rigorously restricts the physical design of the antenna block. Dielectric loaded dipole is the basic GPR antenna as a simple, easy-to-use and linearly polarized structure. Nevertheless, the operational bandwidth and gain response of the dipoles are mostly poor and unsatisfied for high-performance UWB GPR. Therefore, two types of planar antennas, Vivaldi, bow-tie and spiral are more likely to be chosen. Although both have similar electrical and physical characteristics, the main difference is the polarization response. For a circular-shaped object, bow-tie looks more convenient antenna type with linear polarization and better phase response linearity over the wide band.

The vehicle mounted GPR has a physical advantage for antenna design, so that 3-D broadband antennas can be applied. TEM horn, which has mainly bow-tie originated characteristics, is an appropriate structure due to its wider band, higher gain and narrower beam width characteristics It is also available to apply some dielectric loading techniques to improve its antenna pattern. The antenna array configurations can be implemented especially for the vehicle mounted larger GPR systems. In this case, proper RF shielding enclosures should be designed to prevent the coupling between T/R pairs and different receiver antennas, as much as possible[7].

2.3.1 Planar antenna designs

The bow-tie is a dipole-like characterized wide band antenna frequently used for pulse transmission. It shows higher gain and wider band performance than a simple dipole. The spiral has Archimedean and logarithmic models and it is a theoretically frequency independent antenna. But in practice, both spirals have band limitations from the feed radius and the arm length for the upper and lower frequencies, respectively. The impedance matching is another critical point to increase antenna gain efficiency and to reduce time domain ringing effects.

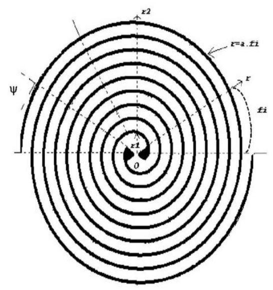

Figure 2.1: Two armed archimedian spiral

Some planar ultra-wideband Vivaldi antennas are introduced for detection using GPR with good performance as compared to conventional TEM horn antenna.An exponential tapered slot edge (TSE) structure with defected

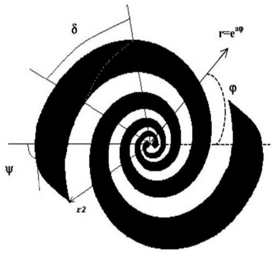

Figure 2.2: Two armed logarithmic spiral

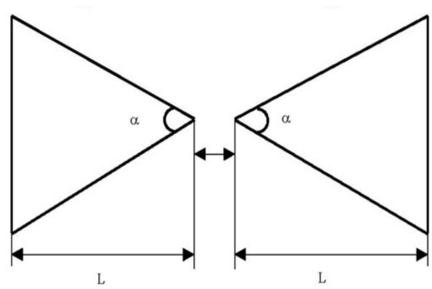

Figure 2.3: Triangular plate Bowtie

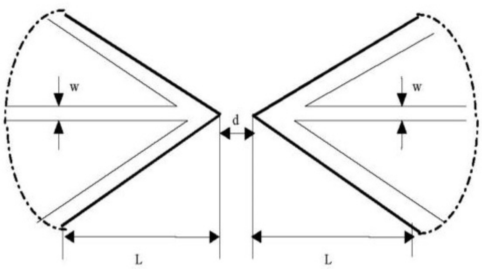

Figure 2.4: Grating model circular Boetie

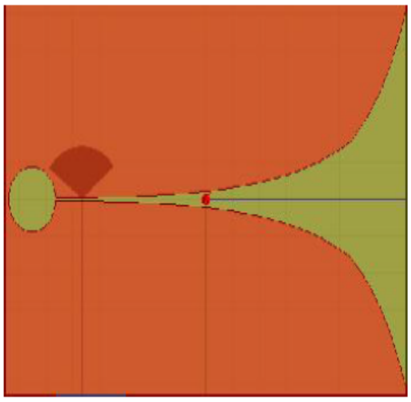

Figure 2.5: Vivaldi Antenna

ground structure as electromagnetic band gap (EBG) is employed.The exponential tapered slot edge (TSE) structure has the advantage of extending the low-end bandwidth limit and improves the antenna matching especially at low frequency. The electrical length of the antenna can be reduced to 40 compared to the original antenna size.

A bowtie antenna is a planar dipole where a broadband behaviour is obtained by using triangular shaped monopoles.With respect to a standard design of a bowtie antenna, it has been demonstrated that a bandwidth enhancement effect can be obtained by using triangular monopoles with rounded corners, coplanar waveguide as feeding lines, loading stubs, etc.

The corresponding layout is illustrated in Fig. 2: the antenna consists of two crossed bowties with rounded corners capacitively loaded with an annular ring.The presence of the ring adds spurious resonances resulting in a very broadband behavior[8].

2.3.2 TEM Horn antenna designs

TEM horn is one of the most promising antennas for impulse GPR systems as a result of its wider frequency band, higher directivity gain, narrower beam width and lower back reflection characteristics than planar antennas. It consists of a pair of triangular or circular slice shaped conductors forming some V-dipole

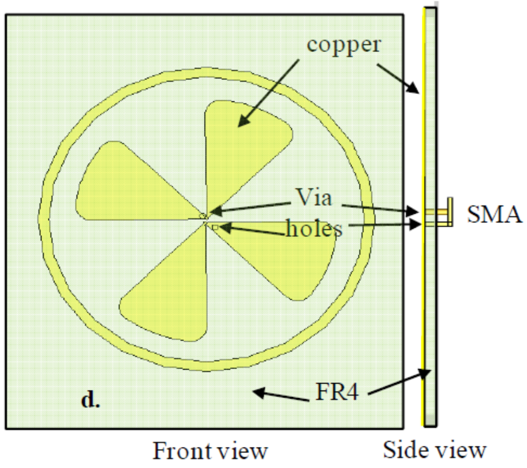

Figure 2.6: Bowtie Antenna

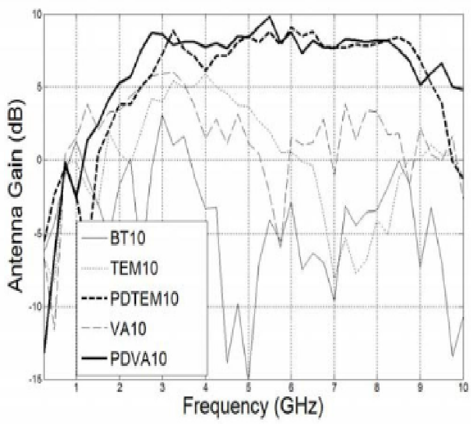

Figure 2.7: Comparision of antenna Gains

structure and characterized by L, d, α and θ parameters which correspond to the length of the antenna, feed point gap, conductor plate angle and elevation angle, respectively (As shown in Figure [2.8])

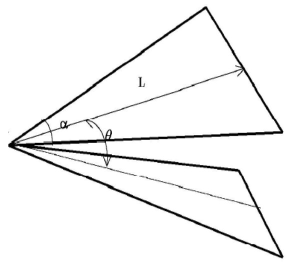

Figure 2.8: TEM Triangular

In general, the arm length of the TEM horn limits the lower cut-off frequency of the radiated pulse, the plate angle designates the determines the structural impedance of the antenna with d and α. A conventional TEM horn antenna usually shows band pass filter-like gain behavior over a large bandwidth. Therefore, dielectric-filling techniques are employed to improve the operational band decreasing the lower cut-off frequency by increasing the electrical size.

The antennas for impulse radar need to fulfill a number of requirements in order to be considered suitable for such systems. The most important thing is to have wideband characteristics with good directivity and radiation efficiency. Although there is a number of antennas that have been used in such systems, the most suitable one seems to be the TEM horn antenna. the TEM horn antenna has been investigated using the multiple quarter-wavelength transformer technique. If two-wire transmission line ,where we have two time varying currents along two electrical conductors in small distance apart ($d << \lambda$) carrying equal in magnitude and opposite in direction currents I_o. Each of these conductors will generate three specific electromagnetic field components, two electric (E_θ and E_r) and one magnetic (H_ϕ). As all the field components are vector quantities, the currents along the two-wire transmission line are equal in magnitude but opposite in direction. Due to this fact, each will generate an electromagnetic field equal in magnitude but opposite in direction. In the far-field, the total electric fields are added vectorially resulting a net radiating power ideally (desired) equal to zero.

The above situation is true for a close spaced (d $<<\lambda$) two-wire transmission line. If this is not the case, and the transmission line begins to flare if (d$\cong(\lambda/2)$) then the fields radiated by them do not cancel out resulting a net radiating power[9].

The antenna consists of flared section and TEM double-ridged transition including a coaxial excitation. The transition section is divided into two parts, a TEM double-ridged waveguide and a cavity back located at the back of the waveguide. Tapering of the two identical ridges is the most significant part in the double-ridged horn antenna design. It is desired that the ridge height and width taper must be such that the associated impedance taper is a smooth transition from the ridge (500) impedance to the impedance of free space (3770) In order to increase the impedance matching between the double-ridged waveguide and the free space, ridges are tapered both laterally and longitudinally, it means that height and width of ridges varies in flared part of horn antenna. Tapering of the ridges in longitudinal plate (y axis) is based on exponential function and in lateral plate (x axis), ridges are tapered linearly[10]. The curvature of the ridges along the longitudinal direction is determined by a modified exponential function as Equation

Equation new design for tapering the flared part of TEM double-ridged

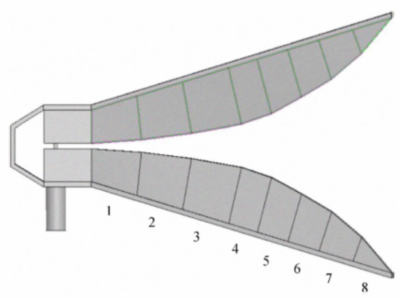

Figure 2.9: Antenna with smooth tapeing

horn antenna leads to a significant size reduction of the device. Furthermore, Stimulation results show that the designed antenna provides good VSWR (less than 2), satisfactory far-field radiation characteristics and high gain over the practical bandwidth.

Among the varying design parameters are linear and exponentially tapered walls as well as variations of the curvature of the dielectric waveguide

Figure 2.10: DRH with dielectric filling

between the two ridges. In addition an absorber structure and a complex shaped metallic back plate have been introduced to further improve the return loss. The primary design goal is a broad bandwidth while maintaining compact dimensions. Two modifications have been introduced in this antenna design in contrast to the standard TEM horn. By protruding the ridges from the aperture plane and filling the space between the ridges with dielectric material it is possible to lower the operating frequency without increasing the size of the original setup.

Horn antennas are mostly used with FMCW surface-penetrating radars where the generally higher frequency of operation is needed and where the requirement for linear phase response is needed.

Certain antennas on the market today are used for electromagnetic compatibility measurements such as radiated immunity and emissions testing. These are designed to cover a broad frequency spectrum while maintaining specified directional properties. However, trying to meet both criteria leads to distortion either in the phase or amplitude properties of the incoming signal. Designing an antenna with desired qualities in the time-domain will translate to an antenna with a broadband response in the frequency domain. A well designed time-domain antenna should accurately reproduce the time waveform of the incoming field, thus preserving the amplitude and phase of the incoming signal to provide desirable time-domain fidelity, an antenna must have both a constant amplitude response and a linear phase response in the frequency domain. Applications for which this characteristic is important include electromagnetic compatibility (EMC) facility evaluations , site attenuation measurements to determine ambient loss , room imaging studies and shielding effectiveness studies on aircraft.

Desirable design characteristics of time-domain TEM horn antennas include constant amplitude, linear phase, and high sensitivity to fields in both the time and frequency domains. The TEM horn antenna is designed to introduce minimal waveform distortion by allowing the fields within the structure to remain in the dominant transverse electromagnetic mode. By designing these antennas specifically for use with impulsive time-domain signals and having a broad frequency spectrum, time-domain distortion can be minimized.

This technical report will discuss the design, construction, measurement and application of several TEM horn antennas. Fore sections describe in detail three TEM horn antennas simulated in CST microwave studio: (1) Linear TEM Horn antenna (2) Double ridged TEM Horn antenna and (3) Compact Double ridged TEM Horn antenna. The physical dimensions of the antenna, the impedance matching into and out of the antenna structure, and the design equations will be discussed in the following subsequent sections.

A TEM horn antenna provides minimum-duration response to impulsive input or output fields and is able to discriminate between events occurring in the time domain. This is done by limiting the amount of propagation modelling in the antenna and by having a good impedance match design both at the feed-point to the antenna and at the aperture of the antenna. Inside the antenna, the fields should remain in the dominant mode, which for our antenna is the TEM mode. In other antennas, such as the log-periodic antenna, the spiral antenna, or the pyramidal horn antenna, phase dispersion occurs as the wave propagates along each of the elements, resulting in a greatly extended antenna response time to the fields. The impulse response of the TEM horn antenna to the input waveform of an impulse generator for a waveform having a pulse width of approximately 300 ps. The TEM horn response time is on the order of a few nanoseconds. We can state that the TEM-horn antenna can accurately reproduce the incoming response of the surrounding environment and can resolve scattering events on the order of approximately 5 ns. The impulse response of a log-periodic antenna is on the order of 40 ns. In this case, if we were trying to localize two events that are 10 ns apart, say reflections from the walls of a chamber, then the TEM horn antenna can discriminate between these events, but the log-periodic antenna cannot. The linear phase response of a TEM horn occurs because the antenna elements maintain the proper field and current relationships, by means of correct width and height ratios. This constant impedance property is a key design criterion for TEM horn antennas. In order to illustrate the linear-phase property, we measured the transmission for TEM horn antennas at various separation distances and plotted the linear phase as shown in Figure 2.11

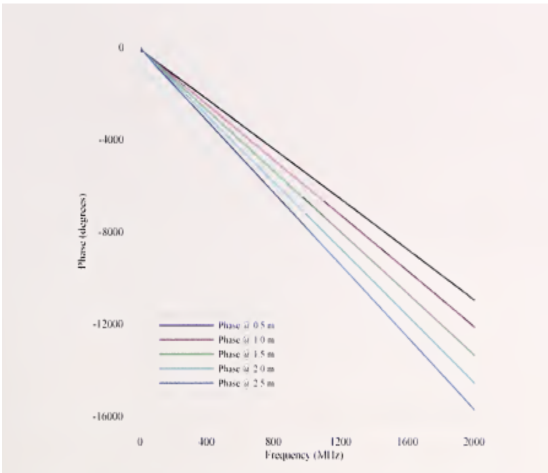

Figure 2.11: Linear phase response of TEM Horn antenna

2.4 Basic TEM Horn Design Principles

Figure [2.12] shows a general drawing of a TEM horn antenna. The width w and height h determine the impedance of the antenna, and a constant w/h ratio maintains constant impedance. The balun is used to convert input unbalanced electrical signals to balanced electrical signals in the antenna, and the resistive taper is used to reduce reflections from the end of the TEM horn section. The following sections describe the design of each part of this antenna. The equations are the microstrip line equation, which are used widely in designing TEM Hron can be expressed as:

$$\frac{w}{d} = \frac{8e^A}{e^{2A} - 2} \quad when \ \frac{w}{d} < 2 \tag{2.1}$$

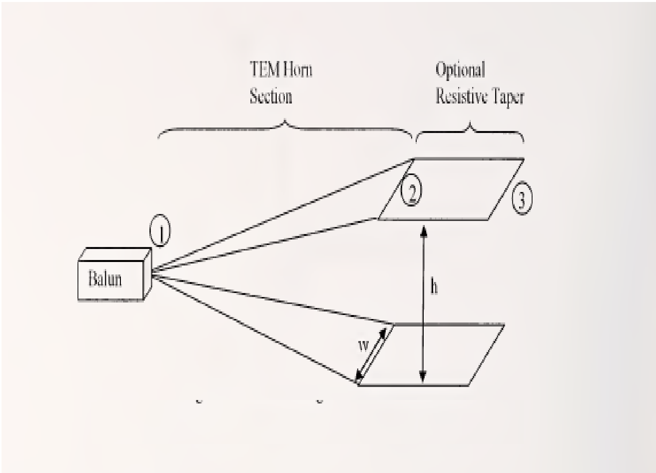

Figure 2.12: General design of basic TEM Horn Antenna

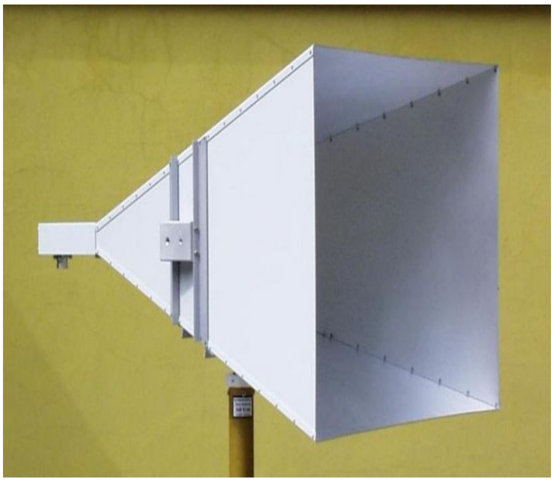

Figure 2.13: Basic TEM horn

$$\frac{w}{d} = \frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right] \; when \; \frac{w}{d} > 2 \tag{2.2}$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) eq : A \tag{2.3}$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} eq : B \tag{2.4}$$

Here we discuss how to design for phase linearity and constant amplitude and how to maximize bandwidth. As mentioned previously, the TEM horn antenna will show phase dispersion if the triangular elements (Figure [2.13]) are not designed correctly. Triangular elements allow current path extremes along the structure, one directly down the center of the element, and the other along the edge. The edge path is obviously the longer, and currents on this path will be delayed. If the delay is large enough, the two signals will arrive at the output 180°out of phase, resulting in a strong reduction in output signal. This phase effect is easy to diagnose since it affects the amplitude response. Usually this will only be a problem only if the triangle is very wide across the aperture compared to its length. An equilateral triangle is as short as practical, but not recommended. Normally our antennas are several times longer than they are wide, and so this phase problem does not occur. Another reason why TEM horn antennas maintain good phase linearity is that the currents in the conductors are moving in the same direction as the electric fields. This is not true in the case of other antennas, such as dipole antennas , A short dipole also maintains linear phase response, but for a different reason; the currents in the structure, although perpendicular to the field, have only a short distance to flow, and therefore respond without delay to the input fields. However, a long dipole does have a noticeable phase problem, because the currents require a significant time to flow down the dipole and the flow in a direction perpendicular to that of the electric field. As a result, the impulse response of a long dipole is greatly extended, resembling a square wave, and having a repetition frequency equal to the resonant frequency of the dipole.

Three conditions must be satisfied for a TEM horn antenna to have constant-amplitude response (see Figure 2.12):

- (1) the impedance of the antenna/balun must be matched to that of the receiver
- (2) the input impedance must be matched to the antenna's internal impedance
- (3) the input and output coupling ot the antenna must minimize resonances and multiple reflections

The amplitude response or antenna factor gives us an indication of the sensitivity of an antenna's response to various frequencies across this bandwidth. Figure [2.14] shows the amplitude response for various antennas, including the TEM horn antenna developed. The antenna factor (AF) is given by

$$AF(dB) = 20.\log \frac{E_{incident}}{V_{received}} \tag{2.5}$$

where the electric field is typically measured at a distance of 1 m. Most of the antennas shown are sensitive to the fields over only a few hundred megahertz (MHz), but the TEM horn antenna factor is constant from approximately 30 MHz to 1500 MHz. Research has shown that an input voltage standing wave ratio (VSWR) of less than 1.2 yields the best impedance match. The components of interest in designing are the input coaxial cable, the balun, the antenna, and the resistive termination.

To achieve a constant antenna factor within the antenna, impedance must be held constant. The TEM horn antennas are designed as parallel plate transmission lines, with a gradual, constant-impedance, tapered transition from the feed-point/coaxial air line at one end, to the aperture dimension of its output at the other end. The impedance of a parallel plate transmission line is a function of the ratio of the width w of the conductive elements to the spacing between the elements h (height). The width to height ratio (w/h) is kept constant by making the elements narrower in proportion to the decrease in spacing. This impedance can be calculated with the microstrip equations of Gardiol or Gupta :

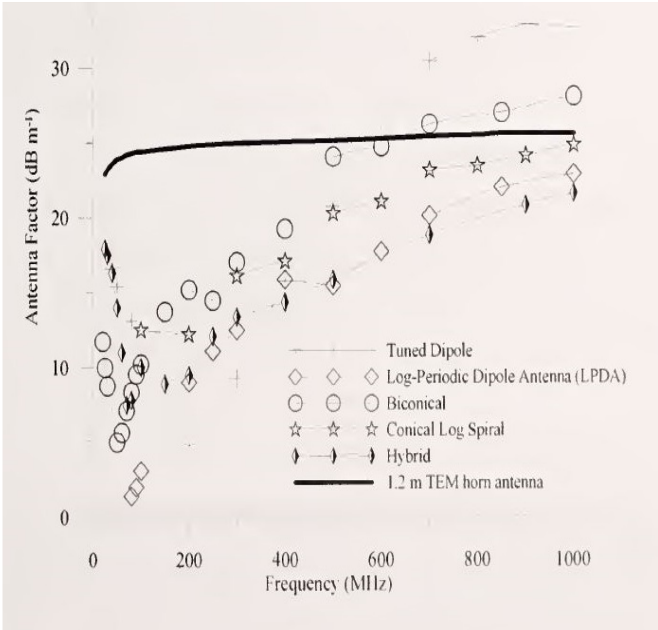

Figure 2.14: Antenna factor for various antenna types

$$Z_o = (\frac{2}{\sqrt{\varepsilon_r}}).52.95.\ln(\frac{8h}{w} + \frac{w}{4h}) \tag{2.6}$$

which is true for 0<w/h <1. i.e.. for antenna impedances greater than 252 *Ω*. The relative dielectric constant is equal to that of Styrofoam (ϵ_r= 1.05). For antennas with impedances between 58.4 *Ω* and 252 *Ω* or 1 < w/h < 10, we use the following equation:

$$Z_o = (\frac{2}{\sqrt{\varepsilon_r}}).376.69.\frac{1}{[(w/h) + 2.42 - 0.44.(h/w) + (1 - (\frac{h}{w})^6)]} \tag{2.7}$$

We used this equation to design an antenna with 50 *Ω* impedance, and it worked very well even though eq.[2.7] was not valid for this impedance value. We note that the equation, as given by Gardiol , is used to calculate the impedance of a micro-strip transmission line, a driven conductor spaced over a ground plane. We use the fact that the driven element has an image in the ground plane, so that the antenna appears to be a micro-strip line with a real conductor in place of the image and with the ground plane removed. This requires only two slight changes:

the impedance of the antenna is twice that of the microstrip, and the spacing between the antenna elements is twice the microstrip height. This is the reason for the two extra factors of 2 above. The antenna has a low-frequency cut-off which is related to the length of the antenna, as determined experimentally.

Estimating dimension of TEM Horn antenna

The impulse-radiation characteristics for ground penetrating radar systems with high-gain and low-input-reflection levels over the operational band are attainable for TEM horns with proper dielectric, absorber, and resistive loadings.

Travelling wave antennas such as the TEM horn (see Fig. [2.8]) are basically formed and terminated long dipoles. These kind of antennas can be analysed by a convenient transmission-line approach which assumes that the antenna is completely composed of a number of transmission-line segments, as illustrated in Figure [2.15]. Every line segment is characterized by its local geometrical and constitutional structure parameters[11]. Staircase modelling, as shown in Figure [2.16], is used for TEM horn analysis and the 3D antenna structure is firstly divided into N number of elementary cells, which are chosen to be locally homogeneous and sufficiently small in wavelength. Then, the structure is reduced to a 1D transmission line with corresponding characteristic impedance Z_o^n , propagation constant β_n, segment length l_n,segment width w_n, and segment height d_n definitions[12]. The input impedance of each line segment is expressed as follows:

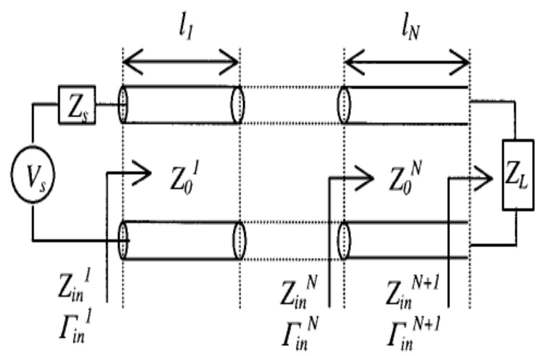

Figure 2.15: Transmission line antenna equivalent model

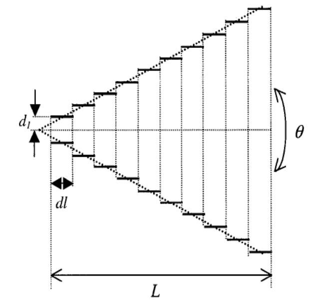

Figure 2.16: stair case modelling of TEM Horn (side view)

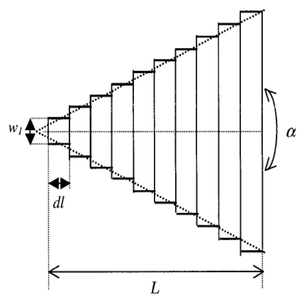

Figure 2.17: stair case modelling of TEM Horn (top view)

where β_n equals the equivalent antenna-line output impedance. The antenna structure is considered as a microstrip line and the partial characteristic impedances of the segments are defined as follows

The input-reflection coefficient of each segment is given by

and the local-reflection coefficients over the nth segment line can be calculated by

The expression in Eq. (4) provides an important advantage for determining the voltage and current distributions over the antenna line more rapidly and stably, without requiring too many numbers of segments.

Designing feed to a TEM Horn antenna

Horn antenna is commonly preferred in most GPR applications because of its directional capability.While designing a directional and wideband horn antenna, the feeder design is an important part in terms of increasing the bandwidth with maintaining the other parameters. In literature, there exist a number of standard feeding types which are used for expanding the bandwidths of antennas. The different feeder types can be used are

- Straight Wire Feeder
- Spherical Feeder
- Conical Feeder

Along with the specific shapes, feeder can be designed by our own. Different feeding techniques will result different bandwidth of operations.Production of the designed antenna is another critical part in which the bandwidth of the antenna can be expanded. Besides the bending and twisting techniques, screw method can further expand the bandwidth of the designed antenna.

Some other applications of TEM Horn antenna

TEM horn antennas can be used in various measurement applications. In each application, we find the TEM antennas useful because of their short-impulse response and linear phase. Other applications of TEM Horn antenna are

- Building-Material Measurements by Use of TEM Horn Antennas
- Aircraft Measurements
- RF Absorber Measurements
- EMC Compliance Chamber Testing
- To measure emissions from common UWB devices in order to determine the interference probability

2.5 Resistive loading technique

HF antennas are matched to multicouplers efficiently by means of discrete, resistive loading. Antennas are loaded by electrically connecting selectively predetermined resistances at various places on the antenna to alter currents thereon and thus vary the input impedance of the antenna. Resistive loading at the apexes far from the feed point and connecting antenna apexes to ground through resistive loading provides maximum energy radiation and reduces energy reflection and undue energy losses.

A short transverse electromagnetic (TEM) horn with continuously tapered resistive loading develops directional reception or transmission of picosecond pulses with minimal distortion. It also creates broadband nature and non-dispersive nature with a low VSWR. With the help of resistively loaded TEM horn receiving transient response waveform of a 70-ps impulse can be well preserved[13].

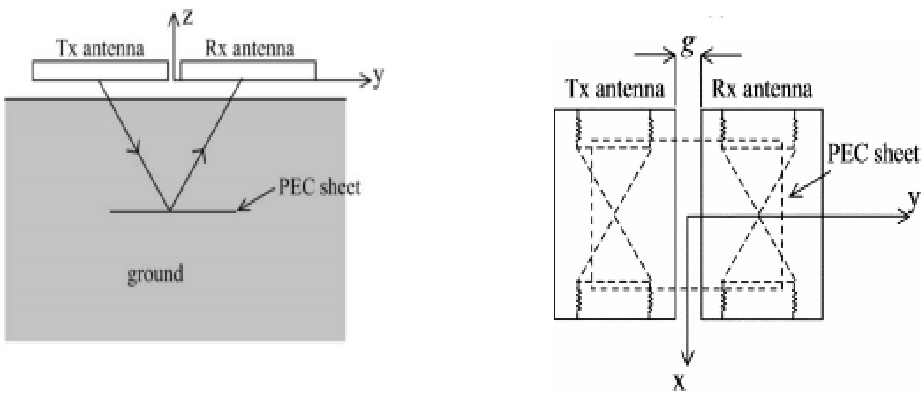

Figure 2.18: Resistive loading to Bowtie

This technique allows transmission of short transient pulses with very small latetime ringing and relatively high radiation efficiency. It makes use of a combination of a constant resistive loading along the antenna and a capacitive loading with linearly increasing reactance toward the antenna ends[14].

The technique can be used advantageously to improve radiation patterns and impedance plots, and furthermore the technique can be extended by means of resistive loaded wires to damp currents on parasitically excited structures thereby resulting in marked improvement of both VSWR and radiation patterns with negligible power loss.

The concept will be described with reference to three methods of loading twin-fan antennas and parasitic structures. In one method, antennas are loaded at the apexes far from the feed-point so that the maximum energy is radiated before energy is dissipated in the form of FR losses by the loading resistors. In this method, a resistor is connected between the apex of the antenna and ground so that energy reflections from the otherwise open end are reduced without causing undue energy loss. In another method, resistive loading is applied at the apex as above and at randomly selected points on the conducting wires of the fan antenna to improve other properties of, the antenna such as increasing the bandwidth thereof. In the third method, apex and random resistive loading as above are used, and furthermore, parasitic structures in proximity to the antenna operationalv environment are resistively loaded to ground.

In general, it can be stated that if the distortion of the currents created by resistive loading does not generate unacceptable nulls in the radiation pattern or reduce the gain of the antenna below a minimum required level, then the technique can be used to advantage. In all three approaches it can be seen that discrete resistive elements are attached to various places on the antenna or on nearby conducting and radiating structures to alter the currents on the antenna and thus change the input impedance.

The short TEM horn with continuously tapered resistive loading receives fast, time-varying, transient fields with minimal pulse-shape distortion due to nonlinear amplitude or phase characteristics of the transfer function.The antenna can be designed for a particular application,i.e.approach can be used in other applications if extremely wide bandwidth and extremely low reflection coefficients are required.

3
Methodology

3.1 Linear TEM Horn antenna (LTEM)

A TEM horn antenna is usually applied to the air-launching GPR system. Traditionally, the variation of characteristic impedance of a TEM horn antenna is usually set to range from 50 Ω (characteristic impedance of a coaxial cable) to 376.7 Ω (free space wave impedance). However, a difference regularly exists between transmission-line wave characteristic impedance and free space wave impedance.There exist no significant difference of performance with the different aperture impedance of the antenna[15].

Because TEM horn antenna is composed of two tapered metal plates, the current flows on these two plates and the TEM wave propagates between these two plates simultaneously. The current flowing on the two plates leads to the generation of the magnetic fields of TEM mode wave. The voltage difference between two plates leads to the generation of the electric fields of TEM mode wave. A TEM horn antenna can be considered to be a transformer from the impedance of a transmission line to the impedance of the free space and the variation of characteristic impedance is usually designed to be between 50 ohms and 376.7 ohms. Since the characteristic impedance variation can be adjusted with the difference of the width of the plates and distance between two plates, the variation of characteristic impedance between two plates has to be calculated carefully in order to make reflection coefficient as small as possible over a large frequency range.In general, there are four main steps in designing a TEM horn antenna. The first step is obtaining the variation of characteristic impedance along the conductor plate. A smooth variation of impedance can keep the reflection from antenna as small as possible. Hecken had derived a function of near-optimum matching section that could provide a smooth impedance variance. Impedance variance can be calculated by the following formulas. The second step is calculating the length of conductor plate. Given the lowest operation frequency and an expected reflection coefficient, the length of conductor plate can be determined.

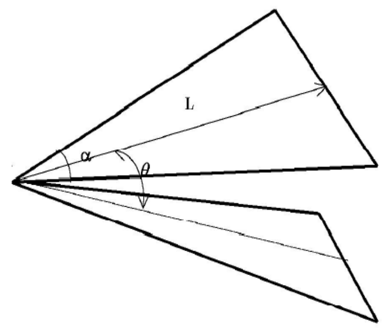

Figure 3.1: TEM Triangular Antenna

The third step is estimating the distance between two conductor plates. There are two main factors in considering the distance between two plates. One is to determine how long the distance between two conductor plates at the feeding point. For the linear taper TEM horn, after the distance of two plates at feed point is determined, next stage is to decide the flare angle between the two conductor plates. The final step is obtaining the width of conductor plate. After obtaining the distance between two conductor plates, the width of conductor plate can be estimated by the parallel microstrip line equations since the variance of characteristic impedance is already known by the first Step.The design equations needed to calculate the dimensions are given by the equations 2.1, 2.2.

A variety of profiles for the cross section of wideband TEM horns, employing an optimal impedance function or exponential taper can be introduced in order to minimize reflection losses[16].Figure shows the performance of TEM Horn with elleptical profile. Based on the tapering how we designed,the performance of the designed TEM horn antenna matching with impedance of 200 Ω may be better than that with free space impedance of 376.7 Ω [15].

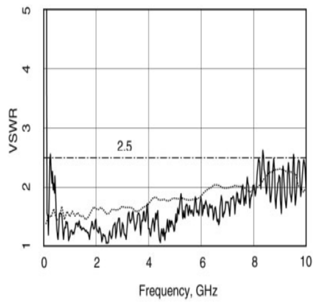

Figure 3.2: VSWR result of TEM Horn with elleptical profile

3.2 Double ridged Horn antenna (TEM DRH)

Another technique to get better VSWR and to get improved gain of antenna is TEM double-ridged horn antenna.By tapering the ridges of antenna both laterally and longitudinally it is possible to extend the operating frequency band while decreasing the size of antenna.

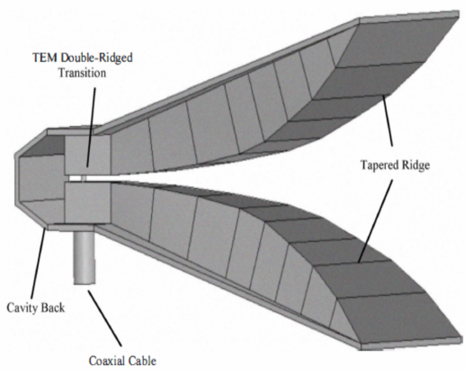

Figure 3.3: TEM DRH antenna

The parameters of the antenna must be optimized using optimization to satisfy the required characteristics. The antenna consists of flared section and TEM double-ridged transition including a coaxial excitation. The transition section is divided into two parts, a TEM double-ridged waveguide and a cavity back located at the back of the waveguide. In order to increase the impedance matching between the double-ridged waveguide and the free space, ridges are tapered both laterally and longitudinally, it means that height and width of ridges varies in flared part of hom antenna. Tapering of the ridges in longitudinal plate (y axis) is based on exponential function and in lateral plate (x axis), ridges are tapered linearly[10]. The curvature of the ridges along the longitudinal direction is determined by an exponential function as follows:

$$Z(y) = 0.02y + Z_0 e^{k.y} \quad (0 \leq y \leq l) \tag{3.1}$$

in which y is the distance from the double-ridged waveguide aperture and l is the axial length (with l = 60mm) of the antenna opening. The k is calculated as follows

$$k = \frac{1}{l} \ln \frac{Z_l}{Z_0} \tag{3.2}$$

wherein Z_o and Z_l is the characteristic impedance at the waveguide and impedance of the hom at the aperture, respectively.

Elimination of radiation pattern deficiencies especially at higher frequencies accompanying with better EM characteristics of the antenna have been the main purposes for these modifications. The main modifications are imposed on the profile of ridges, H-plane flares and E-plane flares. The resulted antenna not only has considerably better performance but also has smaller physical dimensions and less weight in comparison with the conventional one[17].

An exponentially tapered TEM horn antenna with a microstrip-type balun has also been designed. A microstrip-type balun is used to improve the VSWR performance of the TEM horn antenna. The measured result shows that the proposed TEM horn antenna has the frequency band of 67.94 to 1573.9 MHz for VSWR less than 2.0 and the bandwidth of the TEM horn antenna becomes more than three times comparing to that of a linearly tapered TEM horn. It is anticipated that this antenna is applicable to the EMC measurement and broadband communication system[18].

3.3 Quad ridged Horn antenna (TEM QRH)

A compact quad-ridged horn antenna (QRH) for the deep ground penetrating radar applications can be designed to operate in frequency range of 50MHz to 40GHz.

Among the varying horn design parameters, the linear and exponentially tapered walls are studied as well as variations of the curvature of the dielectric waveguide between the two ridges enhancing the matching conditions hence, reducing size and increasing the antenna operational bandwidth. with the design goal of achieving broad bandwidth antenna with maintaining compact dimensions, Two modifications have been introduced on the conventional triangular TEM horn antenna. First multifunction tapering of the horn plates with curvature ending, second inserting perturbing two different ridges between the aperture planes and filling the space between the ridges with high dielectric constant material, in order to lower the operating frequency without increasing the size of the original setup. Replacing the two ridges with four ones, each pair is perpendicular to the other, reduces more the antenna size and improves more its matching.

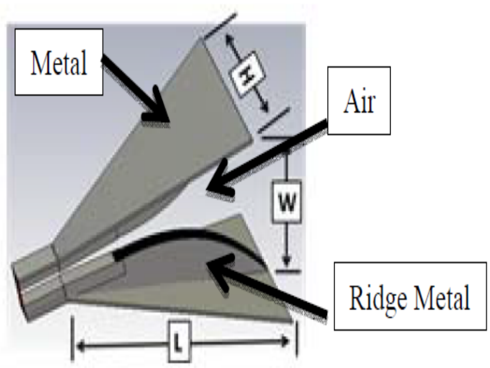

Figure 3.4: TEM QRH antenna

The construction of the TEM horn antenna is divided into two parts, a TEM double/quad-ridged waveguide transition and a flare section of the horn with tapered parallel plates.The TEM double-ridged waveguide transition is divided into two parts, a TEM double-ridged waveguide and a shorting plate (cavity back) located at the back of the waveguide.This antenna presents high gain and efficiency increase.

A dielectric-loaded quad-ridged horn antenna (DQRHA) that operates at 14-38GHz frequency band with dual-polarized character is analysed and simulated for ultra-wideband applications. The dielectric loading method using a perpendicular circular dielectric above the aperture can increase the gain of the quad-ridged horn antenna by 1-1.5dB from 17GHz to 38GHz [19].

Some useful methods for broadband and high gain have been proposed and practiced. Always, modifying the feeding part and changing the shapes of the ridge or horn are two ways to achieve the broadband character. High gain and modified pattern in high frequency band are two pursues for designers who are interested in ridged horn antennas in recent years. Dielectric material loading is always chosen to improve the gain over the operating band.

3.4 Low dimension Horn antennas

In order to achieve required meets without any increase in size of the antenna few more techniques can be used further. An exponentially tapered TEM horn antenna is fed directly by a coax through a compact transition section and possesses a wide bandwidth, good radiation characteristic, and easy integration with microwave circuits. Two specially tapered metal flares have been designed to make a wideband characteristic and reduce the reflection. To overcome aperture reflections at low frequencies and unbalanced aperture field at higher frequencies, an arc surface is added at the end of the flare plates and an absorbing material is loaded on the outer surface of the flare section. Due to this immersion technique golas can be met with smaller size antenna only.

To overcome the splitting in the main lobe and unbalanced aperture field over the higher frequencies and to eliminate the aperture reflections, an arc surface with angle β and radius γ is added to the ends of the horn and an absorbing material is placed on the outer surface of the flare section. To understand the influence of loaded arc surface and absorbing material on the antenna characteristics, the commercial software packages CST has been employed.

A dielectric placed at the aperture can improve the efficiency to 70%.The dielectric lens removes phase errors that exist at the aperture and improves the antenna aperture efficiency.It is well known that single mode horn antennas suffer from poor aperture efficiency due to phase errors (or phase variation from a uniform phase distribution) and amplitude taper that exist at the horn aperture as excited by the fundamental mode. In addition to lengthening or profiling the horn, a dielectric lens can be added to correct the phase taper of the fields at the aperture and improve efficiency. In many situations adding a dielectric lens is more mechanically feasible than lengthening the horn. Also, low weight dielectrics can be used in cases where mass reduction is desirable. Dielectric lenses can also be used to change the aperture phase for the reduction of sidelobes[20].

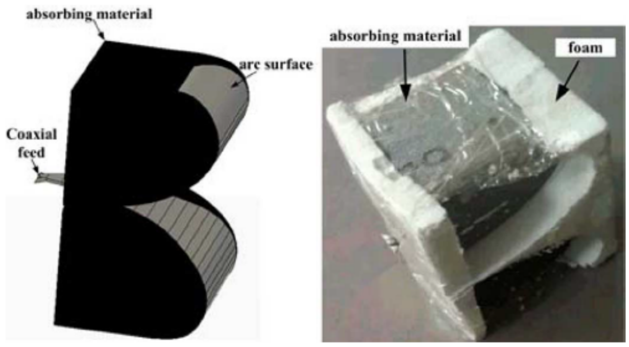

Figure 3.5: TEM Horn immersed in absorbing material

3.5 Final approach adapted

The approach to get higher bandwidth, higher gain & higher directivity in GPR is adopted by TEM Hron antenna.The Compact double ridge horn antenna will result in getting low frequncy when compared to Linear TEM Horn & Double ridged TEM Horn antenna and following with a better feeding design we are able to get better bandwidth.

The approach taken in this design was to develop impedance matching with the help of tapered ridge structure. By using ridge structure one can achieve better VSWR. The final approach in this design is to insert a dielectric medium in between the ridge structure to further decrease the low frequency of operation.

4

Design of Compact TEM Double Ridged Horn antenna

Among all the existing TEM horn antenna types either Compact Double ridged TEM horn or Quad ridged horn will provide better frequency range form a low frequency (<1 GHz) to a higher frequency (>6.5 GHz). In order to find the location and depth of an object, buried subsurface, various types of GPR antenna are used to collect the data. The type of GPR antenna required is dependent on the depth and size of the target to be located.

Goal of design

GPR waves travel through many different materials. Different types of soil, concrete, fill material, debris, and varying amounts of water saturation all have different dielectric and conductive properties that affect the GPR waves, and thus GPR data interpretation.

In most cases an estimated depth range can be determined with accuracy based upon the subsurface material and the frequency of the GPR antenna. For applications requiring higher resolution, such as locating rebar or conduits in concrete, a higher frequency GPR system (1,000 MHz) is used. This will give high resolution detail for down to approximately 24 inches in depth. Applications which require deeper penetration in ground soil requires a lower frequency (12.5 MHz to 500 MHz). Depending on the subsurface material the depth range can be from a few inches to thousands of feet (as indicated in the chart:[1.5]). So in this design the goal is to achieve low frequency with a value at least less than 1 GHz and it should be tuned to a higher frequency with a value greater than 6.5 GHz.

Simulation approach

The following flow chart indicates the step by step design process in this design.

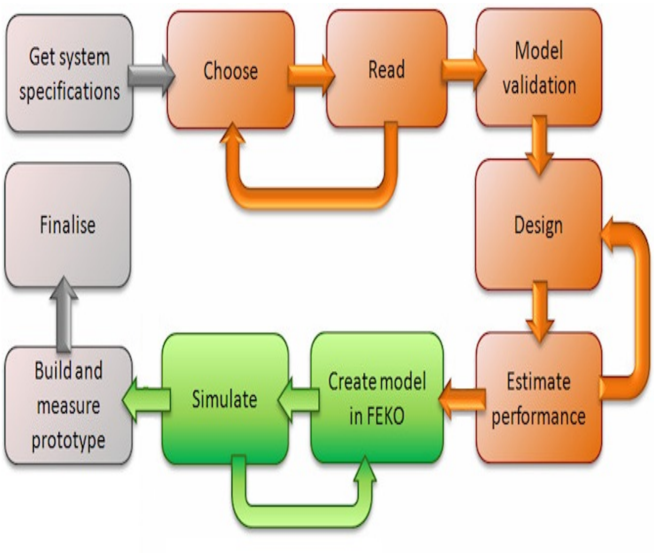

Figure 4.1: Flow chart for simulation design

4.1 Simulation results

4.1.1 Linear TEM Horn antenna (LTEM)

Geometry of proposed antenna:

Figure [4.2] shows the geometry of designed Linear TEM horn antenna, In this design the parallel plate waveguide edges are flared linearly. Due to

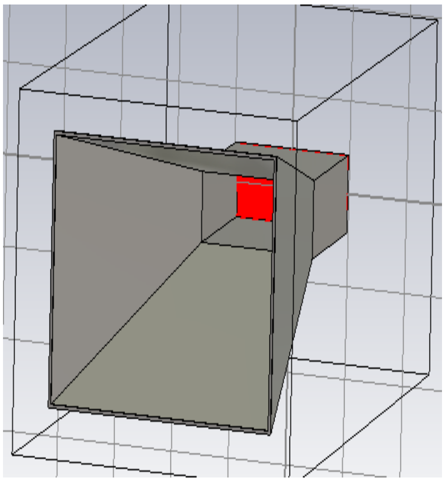

Figure 4.2: Designed Linear TEM Horn antenna

smooth impedance variation from feeding point to aperture mouth, refelctions are minimized. This antenna is fed via waveguide port. The total horn length in this design is 280 mm.

Simulation Results :

The simulation is performed using CST MW Studio 2014. The S11 of designed Linear TEM Horn antenna is shown in Figure [4.3]. It is observed that the impedance bandwidth from 1.62 to 6.5 GHz is achieved. Below 1.62 Ghz this antenna is facing fluctuations in S11 so the frequency part below to this 1.62 Ghz is not considered. the angle of flaring affects the resonance frequencies and the impedance bandwidth of antenna. The antenna gain is plotted in Figure [4.4].It is varied with a value greater than 6.4546 dB. The VSWR is plotted in Figure [4.5].The value of VSWR is less than 2 from 1.62 GHz onwards.

4.1.2 Double ridged TEM Horn antenna (TEM DRH)

Geometry of proposed antenna:

Figure [4.6] and Figure [4.7] shows the geometry of designed Double ridged TEM horn antenna, In this design the parallel plate waveguide edges are flared linearly & ridges are tapered both laterally and longitudinally, it means that height and width of ridges varies in flared part of horn antenna. Due to

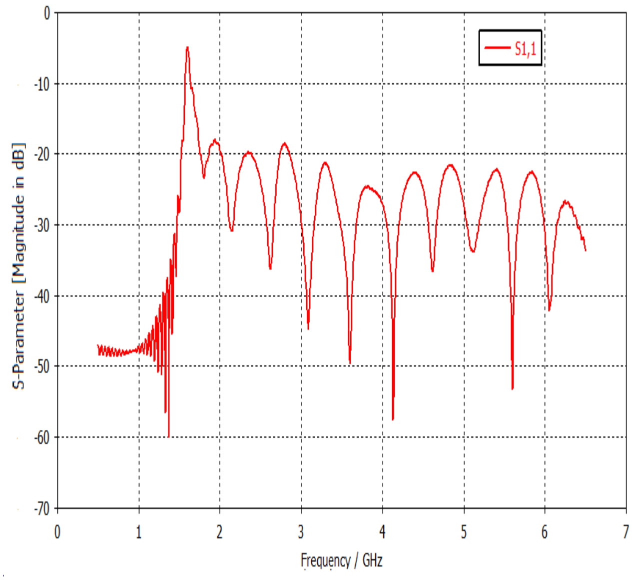

Figure 4.3: Linear TEM Horn-measured S11

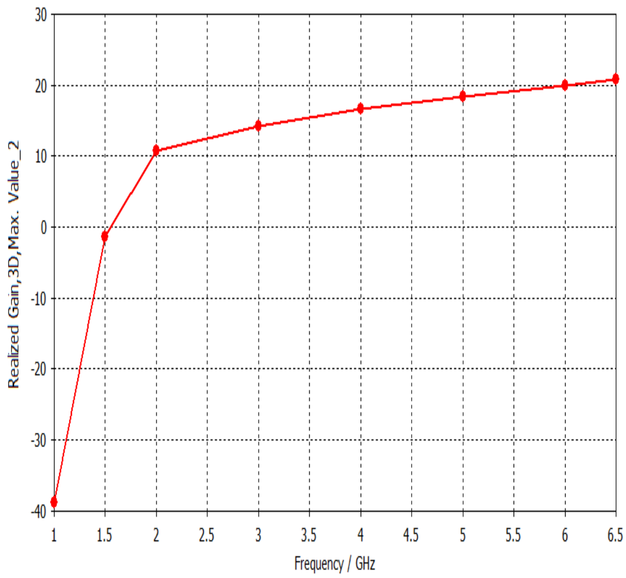

Figure 4.4: Linear TEM Horn-measured Gain

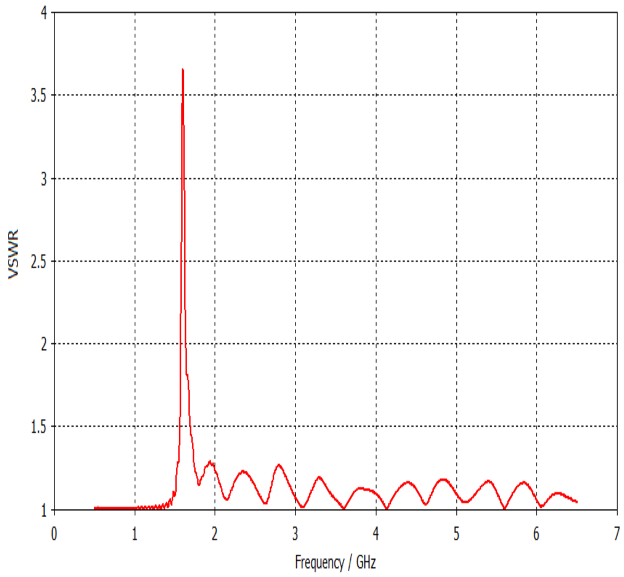

Figure 4.5: Linear TEM Horn-measured VSWR

smooth impedance variation from feeding point to aperture mouth reflection are minimized. This antenna is fed via 50Ω coaxial port. Along with the ridges inserting a stub section in the waveguide decreases the lower cutoff frequency further.

Simulation Results :

The simulation is performed using CST MW Studio 2014. The S11 of designed TEM DRH antenna is shown in Figure[4.8]. It is observed that the impedance bandwidth from 0.927 to 6.5 GHz is achieved. Below 0.927 Ghz this antenna is facing high reflections in S11 so the frequency part below to this 0.927 Ghz is not considered. The angle of flaring & gap between the ridges affects the resonance frequencies and thus the impedance bandwidth of antenna. The antenna gain is plotted in Figure[4.9]. It is varied with a value greater than 10 dB. The VSWR is plotted in Figure[4.10].The value of VSWR is less than 2 from 0.927 GHz onwards.

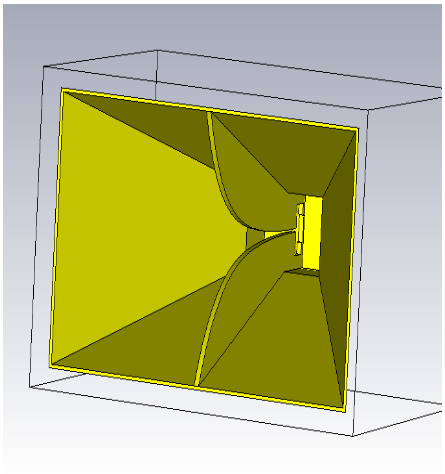

Figure 4.6: TEM DRH antenna-perspective view

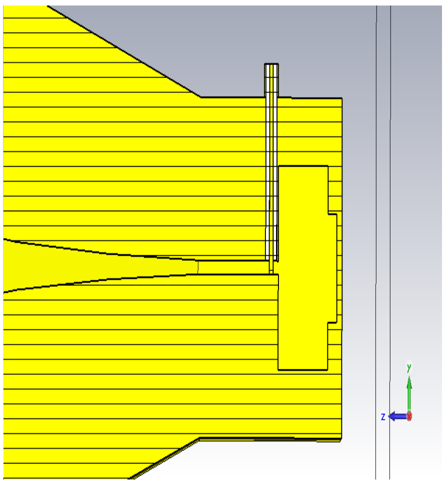

Figure 4.7: TEM DRH-side view of stub

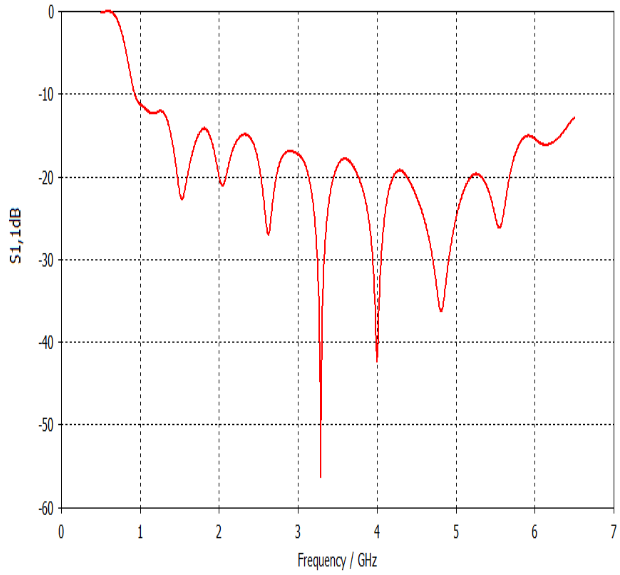

Figure 4.8: TEM DRH-measured S11

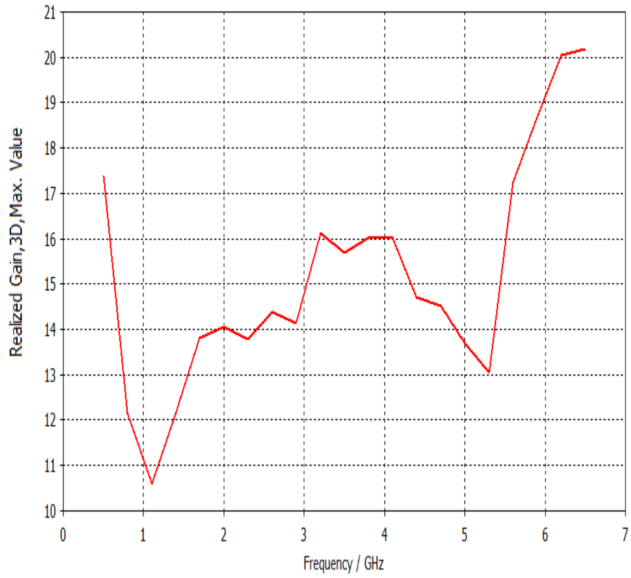

Figure 4.9: TEM DRH-measured Gain

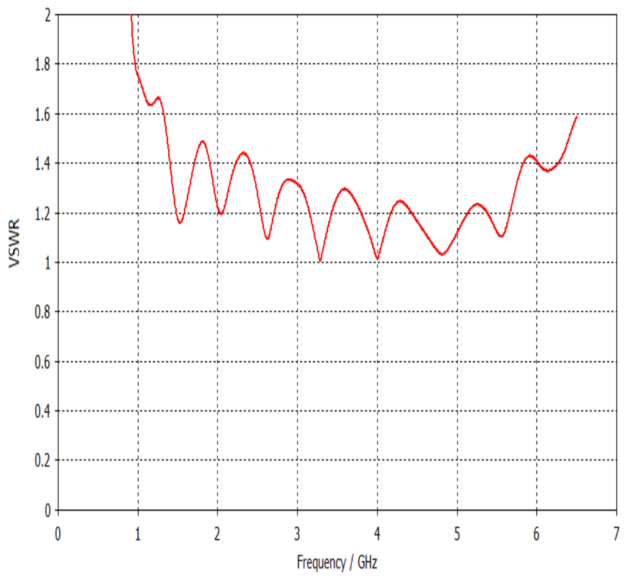

Figure 4.10: TEM DRH-measured VSWR

4.1.3 Compact Double ridged TEM Horn antenna (CTEM DRH)

Geometry of proposed antenna:

Figure[4.11] shows the geometry of designed Compact Double ridged TEM horn antenna, In this design the parallel plate waveguide edges are flared linearly & ridges are tapered both laterally and longitudinally, it means that height and width of ridges varies in flared part of horn antenna. Along with the ridges inserting a dielectric material in between the ridges decreases a the lower frequency further.Due to smooth impedance variation from feeding point to aperture mouth reflections are minimized. This antenna is fed via 50 Ω coaxial port. Along with the ridges inserting a stub section in the waveguide decreases the lower cutoff frequency further.

Simulation Results :

The simulation is performed using CST MW Studio 2014. The S11 of designed Compact TEM DRH antenna is shown in Figure[4.12]. It is observed

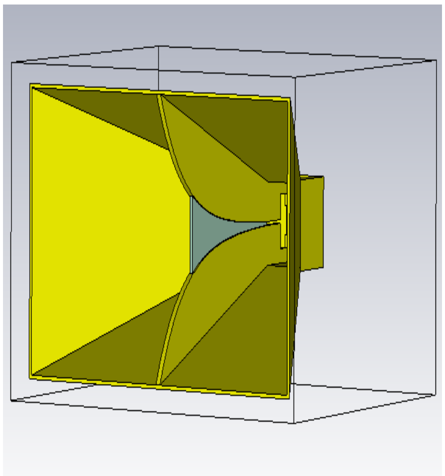

Figure 4.11: TEM DRH with Dielectric in between the ridges

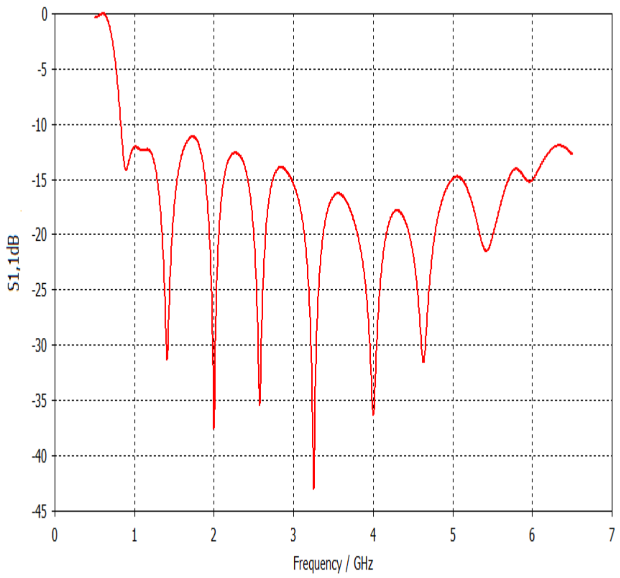

Figure 4.12: Compact TEM DRH-measured S11

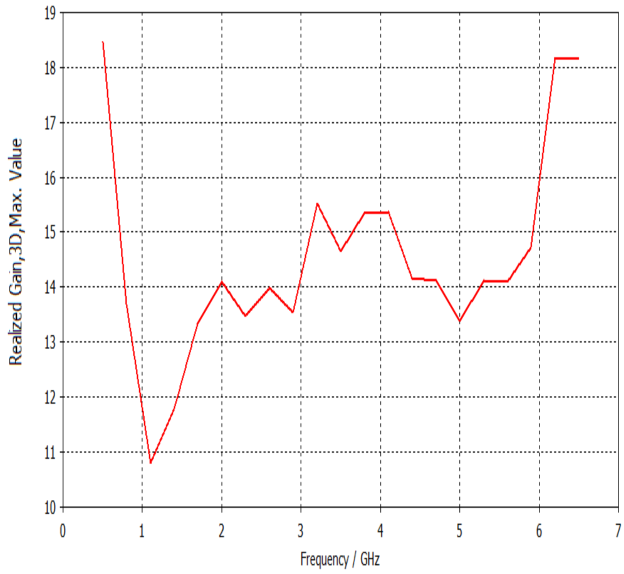

Figure 4.13: Compact TEM DRH-measured Gain

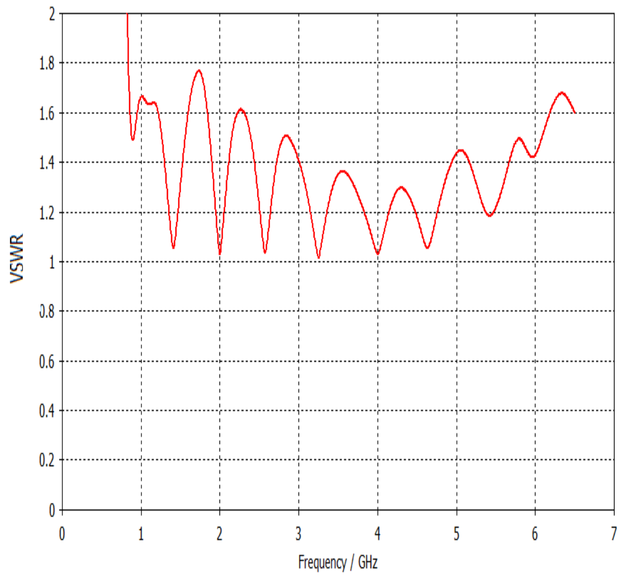

Figure 4.14: Compact TEM DRH-measured VSWR

that the impedance bandwidth from 0.827 to 6.5 GHz is achieved. Below 0.827 Ghz this antenna is facing high reflections in S11 so the frequency part below to this 0.827 Ghz is not considered. The angle of flaring & gap between the ridges affects the resonance frequencies and thus the impedance bandwidth of antenna. The antenna gain is plotted in Figure[4.13]. It is varied with a value greater than 10 dB. The VSWR is plotted in Figure[4.14].The value of VSWR is less than 2 from 0.827 GHz onwards.

4.2 Comparision of results

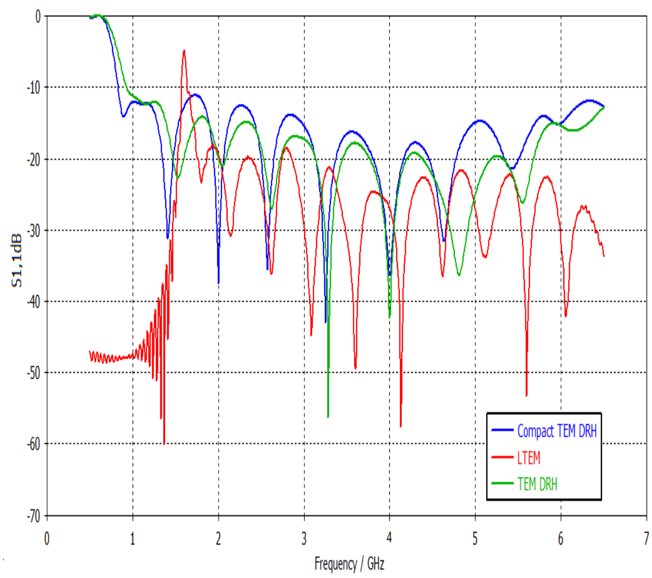

Figure 4.15: Comparision of S11 among all

If we compare the results all the above three antennas the S11 result is far better for Compact TEM DRH antenna. The lower cutoff frequency for LTEM, TEM DRH, Compact TEM DRH are respectively 1.62GHz, 0.927 GHz, 0.827GHz i.e Inserting a dielectric in between the ridges causes the lower cutoff frequency to decrease 1GHz further when compared with TEM DRH antenna.

4.3 Thermal and Mechanical solver simulations

Till now all the simulations are done in CST MW studio in ideal conditions only. Ideal conditions indicate Constant temperature across the body & constant temperature in surrounding part of antenna. Ideal conditions also indicate that the mechanical properties of the antenna body also does not affect the body shape. But what happens if there is a temperature variation both across the body & in surrounding air. What happens if there is mutual temperature exchange in between the antenna body & surrounding. If the temperature variations exist in reality what happens to the structure of the antenna, whether any structural deformation takes place across the structure or it will not show any deformation.

To answer all the questions above the designed antenna is simulated in Thermal solver & Mechanical using CST Multi physics studio and there by concluded that the designed antenna is not prone to thermal & mechanical effects. Figures below shows that S11 result with & without analysis. The scaling factor variation gives the whole system an increase or decrease in the of Thermal & mechanical effects to the antenna body.

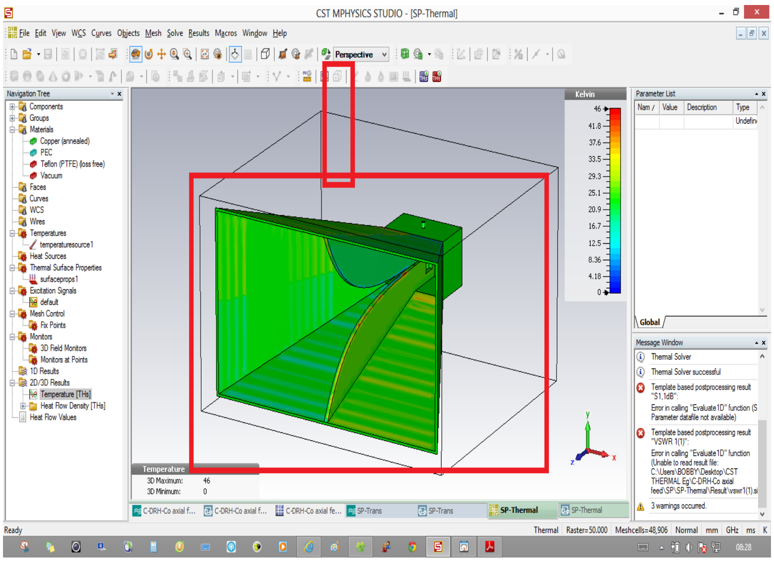

Figure 4.16: Temperature variation across the antenna body

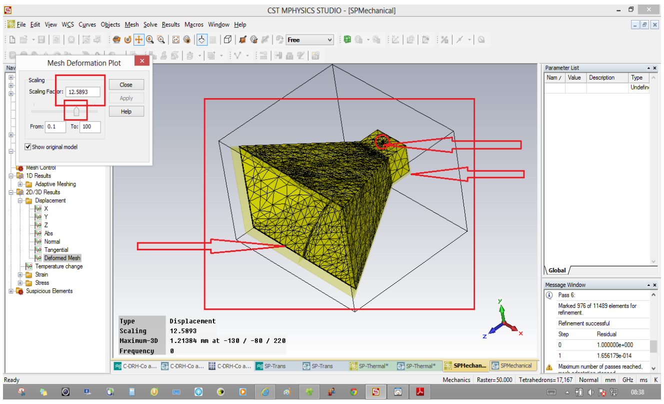

Figure 4.17: Temperature and Mechanical effect on the antenna body

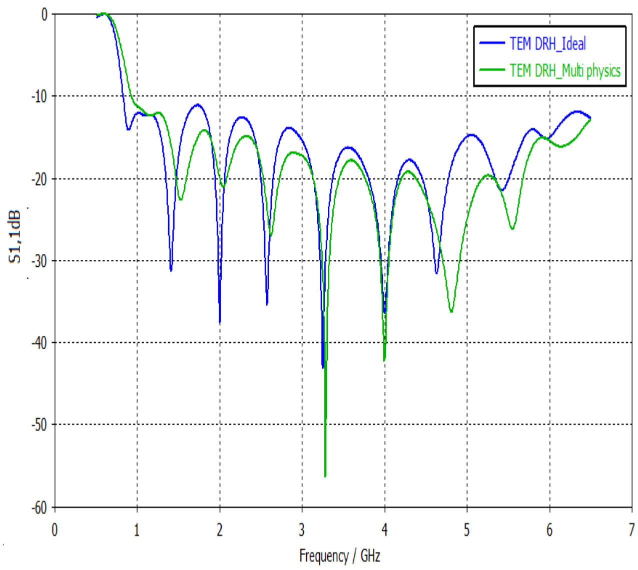

Figure 4.18: Thermal and Mechanical solver analysis on TEM DRH antenna

4.4 GPR scenario in CST MW studio

Designing an antenna suitable for coupling the signal into air is not the goal for GPR antenna. GPR antenna must couple the whole signal completely into ground but not into air. So designing antenna suitable for wireless communication, for Air borne Radar is not the same way in designing an antenna suitable for GPR application. Specific GPR application needs to couple the signal into specific dielectric medium bodies. Figure [4.19] and Figure [4.20] shows the GPR scenario simulation work in CST. This GPR scenario is made up of two sand layers one is dry sand layer (ϵ_r=2.53) & the other is wet loamy soil (ϵ_r=13.8). The top layer is having some thickness where as the bottom layer is infinite in depth. Figure [4.21] shows the S11 result produced by the Compact TEM DRH antenna in GPR scenario. This S11 result is deviating from its original. The lower frequencies of operation is affected when its surrounding resembles reality. So the antenna should be designed specifically for a particular application.

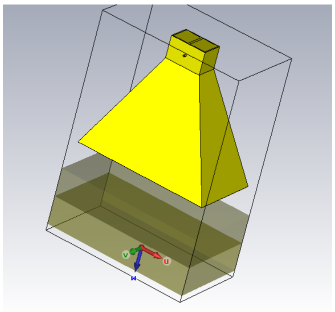

Figure 4.19: TEM DRH in GPR scenario-side view

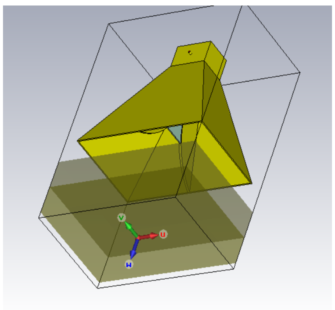

Figure 4.20: TEM DRH in GPR scenario-perspective view

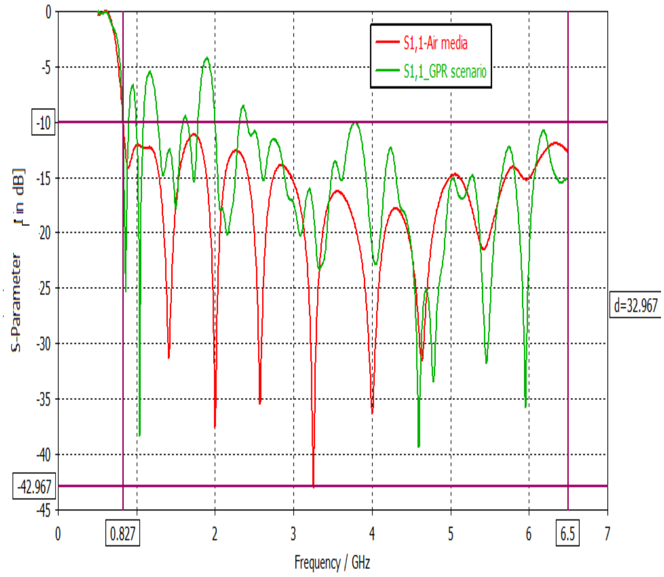

Figure 4.21: Comparision of TEM DRh in Air & Ground media

5
Conclusion

5.1 Conclusion

The design equations, numerical modeling and insight on constructing three ultrawideband, phase-linear, short-impulse response TEM horn antennas are presented. Main challenges faced in designing the antenna are creating a tapered structure to overcome the reflections, choosing antenna dimensions for our requirement, designing stub structure in the waveguide section for minimizing the reflections, designing a feed & choosing a feed location, after all parameter optimization to move closer to our requirement. The Compact TEM Double ridged horn antenna covers the frequency band from 0.927 GHz to 6.5 GHz. The compact TEM Double ridged horn antenna covers the frequency band from 0.827 GHz to 6.5 GHz. The compact TEM Double ridged horn antenna which has a dielectric medium in between the ridges is giving us a low frequency. The achievement with this Compact TEM DRH is that the frequency is lowered by an amount of 1 GHz when compared to TEM DRH. The compact TEM Double ridged horn antenna is appropriate for ground-plane based measurements. The stub design and resistive taper design are important for proper impedance matching, and each design is unique to the antenna, although standardization is possible. Pattern measurements and design modifications have been simulated in a finite-element modeling CST microwave studio environment and have provided insight into measurements and pattern behavior. Finally, various applications were presented showing how these antennas are used in GPR measurements. Because of the favorable characteristics of these types of antennas, we are able to measure in a wide variety of measurement environments.

5.2 Future work

Designing an antenna suitable for coupling the signal into air is not the goal for GPR antenna. GPR antenna must couple the whole signal completely into ground but not into air. So designing antenna suitable for wireless communication, for Air borne Radar is not the same way in designing an antenna suitable for GPR application. Specific GPR application needs to couple the signal into specific dielectric medium bodies. Figure [4.21] shows the S11 result produced by the Compact TEM DRH antenna in GPR scenario. This S11 result is deviating from its original. The lower frequencies of operation is affected when its surrounding resembles reality. So the antenna should be designed specifically for a particular application. By using resistive loading techniques the affect on the antenna at lower frequencies can be reduced further.Using CST MW studio itself performance analysis of antenna in GPR scenario can be carried out.By including the resistive loading technique reflections at antenna aperture can be further minimized.

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